AN ENERGY EVALUATION OF CROP ROTATIONS IN SOUTHWESTERN SASKATCHEWAN

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INTRODUCTION

The Swift Current Research Station's long-term crop rotation experiment, established in 1966, is undergoing detailed evaluation. Papers that summarize yield and grain protein considerations (Campbell et al. 1983b), nitrate-N distribution in the soil and N uptake by the plants (Campbell et al. 1983a), bicarbonate-P distribution in the soil and P uptake by the plants (Campbell et al. 1984a), and economic returns (Zentner et al. 1984) have been completed. In this paper, the energy considerations of the 12 crop rotations included in the experiment are discussed. Inputs of non-renewable energy, energy output, net energy produced, and energy efficiency levels of the crop rotations are examined and compared using data collected over the period 1967 to 1978.

MATERIALS, METHODS, AND ASSUMPTIONS

Twelve crop rotations considered potentially suitable for southwestern Saskatchewan (Table 1) were established in 1966 on 81 plots (each 0.04 ha in size) in a three-replicate experiment. Prior to the experiment, the area had been in a fallow-wheat rotation since 1922. The soil was a Wood Mountain loam (Orthic Brown Chernozem).

Stubble-mulch tillage techniques, with commercially available equipment, were used in the management of the rotations. An average of 3.3 tillage operations (ranging from 2 to 5 operations) with a heavy-duty cultivator and/or rodweeder, plus a late fall application of 2,4-D ester herbicide, were required to control weeds on summerfallow areas. On cropped areas, seedbed preparation generally consisted of one operation with a heavy-duty cultivator with rodweeder attachment. The plots were seeded with a hoe-press drill at the recommended rates of 67, 31, 63, and 76 kg/ha for spring wheat, flax, fall rye, and oats, respectively. Seeding took place generally in early May, except for rye which was usually sown in the first week of September. Ammonium nitrate fertilizer (i.e., 34-0-0) was broadcast prior to seeding and monoammonium phosphate fertilizer (i.e., 11-48-0) was placed with the seed according to treatment specifications (Table 1) and in accordance with the general recommendations of the Saskatchewan Soil Testing Laboratory. Herbicides (i.e., bromoxynil and MCPA, 2,4-D ester, triallate, diclofop methyl, and glyphosate) were applied as required for in-crop weed control using recommended methods and rates. The continuous-type rotations generally received more N fertilizer and more herbicides than the less intensive crop rotations.

Table 1. Crop rotations and treatments

Rotation number	Rotation	Comments
1	Fallow-wheat-wheat	P applied, but no N applied
2	Fallow-wheat-wheat	N and P applied
3	Fallow-flax-wheat	N and P applied
4	Fallow-fall rye-wheat	N and P applied
5	Fallow-wheat-wheat	N applied, but no P applied
6	Oat hay-wheat-wheat	N and P applied
7	Flax-wheat-wheat	N and P applied
8	Continuous wheat	N and P applied
9+	Continuous wheat	[fallow if less than 60 cm of moist soil at planting time, otherwise crop] N and P applied
10+	Continuous wheat	[fallow if grassy weeds become a problem, otherwise crop] N and P applied
11	Fallow-wheat	N and P applied
12	Continuous wheat	P applied, but no N applied

+ Rotations 9 and 10 were cropped continuously because the criteria necessary for fallowing (see comments) did not occur during the 12-year study period.

Plots were harvested at the full ripe stage, except for oat hay. Each plot was windrowed and the grain yields determined by threshing the seed with a conventional combine. The straw and plant residue were distributed back on the plots by a paddle-type spreader attachment on the combine. Oat hay was cut at the soft dough stage and dried naturally, baled, and weighed. After harvest, all seeded plots received an application of 2,4-D ester herbicide at the recommended rate to control winter annual weeds.

Information on the type and frequency of field operations performed, machines and equipment used, types and amounts of herbicides and fertilizers applied, and crop yields obtained in the experiment for each rotation treatment, replicate, and year were used as input data for the energy evaluation. Fuel use asociated with the field operations was not measured in the experiment. Estimates were made using empirical relationships that relate fuel use to power requirements of the specific machines (Zentner et al. 1983). Recommended depths of tillage (where appropriate) and forward speeds were assumed for all field operations.

The physical quanities of inputs used in production were converted to energy values using energy coefficients taken from the literature (Table 2). Both direct and indirect energy expenditures were included. Energy invested in machinery and in grain and machine storage buildings (including maintenance and depreciation) was amortized over the expected useful life of the capital items (Jensen 1977). No allowance was made for the energy removed from the soil in the form of plant nutrients, nor for that which was captured directly from the sun by the plants. Furthermore, no allowance was made for home or personal energy consumption.

Table 2. Energy coefficients for agricultural inputs and outputs

Agricultural input/output	Energy coeff.	Unit of meas.	Data Source
Variable inputs			
Gasoline	41.2	MJ/L	Southwell and Rothwell (1977)
Diesel	45.2	MJ/L	Southwell and Rothwell (1977)
Lubricants	43.8	MJ/L	Southwell and Rothwell (1977)
Nitrogen fertilizer	89.1	MJ/kg	Leach (1976)
Phosphorus fertilizer	15.6	MJ/kg	Leach (1976)
Bromoxynil and MCPA	295.0	MJ/kg of AI†	Boerma et al. (1980)
2,4-D ester	202.0	MJ/kg of AI	Boerma et al. (1980)
Triallate	231.0	MJ/kg of AI	Boerma et al. (1980)
Diclofop methyl	328.0	MJ/kg of AI	Boerma et al. (1980)
Glyphosate	461.0	MJ/kg of AI	Boerma et al. (1980)
Fixed inputs			
Powered machines	9.9	MJ/kg/yr	Jensen (1977)
Non-powered machines	6.8	MJ/kg/yr	Jensen (1977)
Trucks	11.0	MJ/kg/yr	Jensen (1977)
Grain storage bldgs.	13.8	$MJ/m^3/yr$	Jensen (1977)
Machine storage bldg.	153.0	$MJ/m^2/yr$	Jensen (1977)
Outputs			
Wheat	13.8	MJ/kg	Southwell and Rothwell (1977)
Fall rye	14.0	MJ/kg	Southwell and Rothwell (1977)
Flax	9.2	MJ/kg	Southwell and Rothwell (1977)
Oats	10.4	MJ/kg	Southwell and Rothwell (1977)
Oat hay‡	0.73	MJ/kg	Southwell and Rothwell (1977)

† AI = Active ingredient

‡ Oat hay was converted to total metabolizable energy for humans at the rate of 7.261 MJ/kg of beef produced and a feed conversion ratio of 10:1.

For all crops except oat hay, energy output was taken to be the total metabolizable energy of the grain (less seed requirements) for human consumption (Table 2). No allowances were made for the straw and crop residue products because of the need to return them to the land to maintain soil productivity and to provide protection against soil erosion. Oat hay was assumed to be an input to beef production which was subsequently slaughtered for human consumption. A feed conversion ratio for oat hay of 10:1 was assumed for the beef animals (National Academy of Sciences 1970). The energy content of the oat seed was also subtracted from the energy output of the oat hay production system.

Each rotation was evaluated in terms of total and selected categories of energy inputs, energy output, net energy produced (i.e., energy output minus energy input), and energy output/input ratios. Rotations 9 and 10 were treated as additional replicates of rotation 8 because the criteria necessary for fallowing did not occur during the 12-yr study period (Table 1). The results are reported on a per unit of cultivated land basis and include adjustments for the proportions of crop and sumerfallow in the rotations.

RESULTS AND DISCUSSION

Energy Inputs

Total input of non-renewable energy increased as the proportion of summerfallow in the rotation decreased (Table 3). The continuous wheat rotation receiving recommended rates of N and P fertilizer had the highest energy requirement, while the traditional 2-yr fallow-wheat rotation had the lowest. The continuous-type rotations with N and P fertilizer applied required about twice the energy input as for the fallow-wheat rotation. The 3-yr rotations with N and P fertilizers applied required from 11 to 26% more energy than that required for the fallow-wheat rotation.

Table 3. Total non-renewable energy input

Rotation number	Rotation	Fertilizer† N	Fertilizer† P	Mean‡ energy input (MJ/ha)	Standard deviation (MJ/ha)	Index of§ mean energy input
1	F-W-W	0	√	3249c	211	104
2	F-W-W	√	√	3765bc	401	120
3	F-Flx-W	√	√	3937b	641	126
4	F-Rye-W	√	√	3465bc	374	111
5	F-W-W	√	0	3492bc	693	112
6	O(hay)-W-W	√	√	6130a	2097	195
7	Flx-W-W	√	√	5958a	1914	190
8,9,10	Contin.W	√	√	6413a	2224	205
11	F-W	√	√	3132c	240	100
12	Contin.W	0	√	4292b	1067	137

† √ indicates the application of recommended rates of N or P fertilizer. 0 indicates no application of N or P fertilizer.
‡ Means followed by the same letter do not differ ($P < .05$).
§ The mean energy input for the fallow-wheat rotation was used as the index base (i.e., index = 100).

Substituting flax, fall rye, or oat hay for wheat in the 3-yr and in the continuous-type rotations did not significantly change the total energy requirements of the respective rotations. Total energy requirements were reduced by about 14 and 33% when no N fertilizer was applied to the 3-yr and continuous wheat rotations, respectively.

Similarly, failure to apply P fertilizer to the 3-yr wheat rotation reduced the total energy requirement by about 7%. The annual variation in total energy inputs was highest for the continuous-type rotations and lowest for the 2-yr wheat rotation and for the 3-yr wheat rotation receiving only P fertilizer.

Fuel (including lubricants) and fertilizers were the major energy inputs of the rotations (Table 4). Fuel use did not differ greatly among the rotations. This occurred because as the proportion of summerfallow in the rotation declined, the savings in fuel from the reduced summerfallow activities was offset by the increased fuel requirements for planting and harvesting of the additional cropped area. Energy expenditures for fuel represented from 28% of the total energy input for the well-fertilized continuous wheat rotation to 53% for the fallow-wheat rotation.

Table 4. Energy input by resource category†

Rotation number	Rotation	Fert. N	Fert. P	Fuel & lubricants MJ/ha	Fuel & lubricants %	Fertilizers MJ/ha	Fertilizers %	Herbicides MJ/ha	Herbicides %	Capital items MJ/ha	Capital items %
1	F-W-W	0	√	1672	51.5	518	15.9	183	5.6	871	26.8
2	F-W-W	√	√	1686	44.8	1015	27.0	187	5.0	872	23.2
3	F-Flx-W	√	√	1666	42.3	993	25.2	407	10.3	866	22.0
4	F-Rye-W	√	√	1486	42.9	995	28.7	108	3.1	872	25.1
5	F-W-W	√	0	1678	48.0	614	17.6	326	9.3	870	24.9
6	O(hay)-W-W	√	√	1802	29.4	2644	43.1	808	13.2	869	14.2
7	Flx-W-W	√	√	1752	29.4	2426	40.7	902	15.1	871	14.6
8,9,10	Contin.W	√	√	1776	27.7	2878	44.9	876	13.6	877	13.7
11	F-W	√	√	1646	52.5	451	14.4	161	5.1	869	27.7
12	Contin.W	0	√	1738	40.5	776	18.1	898	20.9	874	20.4

†Percentages refer to the proportion of the total energy input.

Energy requirements for fertilizers, particularly N fertilizer, increased by more than 5-fold as cropping became more intensive. This was a result of the higher rates of N fertilizer that were required for wheat grown on stubble as compared to wheat grown on fallow. It reflects the build-up of soil N that occurred on summerfallow areas (Campbell et al. 1983b). The application of recommended rates of N and P fertilizers represented from 14 to 45% of the total energy input of the rotations.

Herbicide use also increased as cropping became more intensive because of the greater need to control grassy weeds. Energy expenditures on herbicides constituted from 5 to 21% of the total energy requirements of the rotations. Energy useage associated with the capital items was similar among the rotations, but accounted for the greatest share of the total energy input for the rotations that included summerfallow.

Energy Output

Total energy output generally increased as the proportion of summerfallow in the rotation decreased because of the greater annual grain production per unit area (Table 5). The continuous wheat rotation with N and P fertilizers applied had the highest energy output, while the fallow-flax-wheat rotation had the lowest. Energy output for the fallow-wheat rotation ranked second lowest.

Within the continuous-type rotations receiving N and P fertilizer, substituting oat hay or flax for wheat reduced energy output by about 30%. Similarly, within the 3-yr rotations receiving N and P fertilizer, substituting flax for wheat or fall rye reduced energy output by about 39%. These results follow from the relatively low yields of flax that were recorded in the experiment (Campbell et al. 1983b) and the low metabolizable energy content of flax and oat hay for human consumption. Failure to apply N fertilizer to the 3-yr and continuous wheat rotations decreased energy output by 6 and 12%, respectively. Similarly, failure to apply P fertilizer to the 3-yr rotation decreased energy output by 12%. The annual variability in energy output was highest for the more intensive crop rotations because of the greater yield variability.

Net Energy Produced and Energy Efficiency

Net energy produced (i.e., energy output minus energy input) was highest for the continuous wheat rotation with N and P fertilizers applied, and lowest for the 3-yr rotation that included flax (Table 5). Net energy produced for the traditional fallow-wheat rotation ranked fourth lowest. The 3-yr and continuous wheat rotations with N and P fertilizers applied produced 20 and 32% more net energy than the comparable 2-yr wheat rotation, respectively. Net energy produced was increased by the application of P fertilizer, but was unchanged by the application of N fertilizer.

Table 5. Energy output, net energy produced, and energy efficiency

Rotation number	Rotation	Fert. N	Fert. P	Mean† energy output – – MJ/ha	Std. dev. – –	Index‡ of mean energy output	Net energy produced MJ/ha	Energy† output/ input ratio
1	F-W-W	0	√	13780cd	4633	113	10531	4.24a
2	F-W-W	√	√	14633bc	4695	120	10868	3.89a
3	F-Flx-W	√	√	8689e	3682	71	4752	2.21c
4	F-Rye-W	√	√	14055cd	4987	116	10590	4.06a
5	F-W-W	√	0	12867cd	4226	106	9375	3.68a
6	O(hay)-W-W	√	√	12732cd	4650	105	6602	2.08c
7	Flx-W-W	√	√	12856cd	4301	106	6898	2.16c
8,9,10	Contin.W	√	√	18309a	5717	151	11896	2.85b
11	F-W	√	√	12157d	3599	100	9025	3.88a
12	Contin.W	0	√	16125b	5595	133	11833	3.76a

† Means followed by the same letter do not differ ($P < .05$)

‡ The mean energy output for the fallow-wheat rotation was used as the index base (i.e., index = 100)

Energy efficiency of the rotations, as measured by the energy output/input ratio, ranged between 2.08 for the rotation that included oat hay and 4.24 for the 3-yr wheat rotation that received only P fertilizer (Table 5). In contrast to net energy produced, the energy output/input ratios for the 2-yr and 3-yr wheat rotations with N and P fertilizer applied were higher than for the comparable continuous wheat rotation. The application of N and P fertilizer to the 3-yr wheat rotation did not significantly change the energy output/input ratios. For the continuous wheat rotation, the application of N and P fertilizer signficantly reduced the energy output/input ratio compared to when only P fertilizer was applied. This was due to the high energy requirement that is associated with the production of the N fertilizer input.

CONCLUSIONS

The results from the Swift Current long-term rotation experiment have shown that the input of non-renewable energy and the output of metabolizable energy for human consumption were directly related to the intensity of cropping. The traditional fallow-wheat rotation used by producers required the least input of non-renewable energy. This occurred because summerfallowing acts as a partial substitute for fertilizers and herbicides. A movement to more intensive crop rotations in the Brown soil zone will require the input of additional non-renewable energy and, under some circumstances, could require a doubling of the total energy input. Fertilizer, particularly nitrogen, will be the major energy input affected by a movement to more intensive cropping. Energy expenditures on herbicides will also increase because of the greater need to control grassy weeds. Energy expenditures on liquid fuels will not change greatly because the extra fuel required to plant and harvest the additional crop is largely offset by the fuel savings from reduced summerfallow tillage.

Annual energy output for human consumption could be increased by as much as 51% by the adoption of more intensive crop rotations. The continuous wheat rotation with recommended rates of N and P fetilizers provides the greatest energy output. However, the energy output/input ratio for this rotation is below that of comparable 2-yr and 3-yr rotations. This suggests that further research is needed to develop technologies that reduce the input of non-renewable energy (e.g., inclusion of legumes, green manuring, minimum tillage), improve the efficiency of energy use (e.g., improved fertilizer placement), and/or increase the energy output (e.g., snow trapping) of the more intensive cropping systems.

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